Chapter 18

High Efficiency Sweeping as an Alternative to the Use of Wet Vaults for Stormwater Treatment

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In May, 1996, the Port of Seattle contracted with Kurahashi & Associates, Inc. (KAI) to conduct an evaluation of selected stormwater treatment best management practices (BMPs) for the Port's marine terminals. The study's objective was to evaluate the stormwater pollutant removal effectiveness of new high efficiency pavement sweepers in combination with conventional sediment trapping catchbasins and to determine if this combination technology is essentially equivalent to the pollutant removal efficiencies of wet vaults. For new marine facilities, the only stormwater treatment BMP that is deemed technically feasible and currently approved by the Department of Ecology is the wet vault.

The type of Port facilities for which sweeping and sediment trapping catchbasins were evaluated is the cargo container yard. The Port currently owns five such facilities covering a total area of approximately 400 acres (160 ha). The Port is currently undertaking major expansion projects at two of the five yards.

The project of immediate interest is the Southwest Harbor Project. This project, currently under construction, will expand an existing container yard by 250 acres(100 ha). Wet vaults are estimated to have a life cycle cost of about $18 million for this expansion project due primarily to the structural requirements of the vault covers that need to fully support large, heavy container transport vehicles called *top picks*. In contrast, high efficiency weekly pavement sweeping with normal sediment trapping stormwater inlets cleaned annually will have a life cycle cost of approximately $2 million for the same expansion project.

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The Port was motivated to evaluate sweeping because of the results of recent studies conducted by KAI (Sutherland and Jelen, 1996b and 1997). These recent studies have concluded that high efficiency sweepers and sweeping operations can provide significant reductions in various pollutants being transported in stormwater. These conclusions are in sharp contrast to the conclusions reached in 1983 by the US Environmental Protection Agency (EPA) sponsored Nationwide Urban Runoff Program (NURP). *(In this chapter $ = US$).*

18.1 Previous Research

The NURP studies of street sweeping effects on stormwater quality (USEPA 1983) concluded that street sweeping was largely ineffective at reducing the event mean concentration (EMC) of pollutants in urban runoff. This conclusion was reached mainly because the street sweepers tested were not able to effectively pick up very fine, highly contaminated sediments that accumulate on impervious areas such as streets, driveways and parking lots. These same sediments, located on paved areas that are directly connected to a city's storm drainage system, have been identified over and over again as the primary source of urban nonpoint pollutants entering the receiving waters of the United States.

However, recent studies by KAI staff over a period of four years show clearly that the NURP conclusions from the early 1980s are today no longer valid. This is largely because of the considerable increase in street sweeping's effectiveness at removing the smallest particles. The reader is referred to Sutherland and Jelen (1997) for a description of the recent street sweeper pickup performance monitoring and modeling that has been conducted.

18.2 Data Collection Program

The general approach to the study was to obtain data that described the rate of pollutant accumulation on an existing container yard. The collected data would then be used to calibrate a computer model that could simulate the washoff of sediment and its associated pollutants and the effect of the various alternative control technologies on the actual pollutant loadings.

The Port of Seattle's T-5 Yard was selected for the data collection program. The T-5 Yard was visited by the project team in late May of 1996. The project team consisted of Port of Seattle staff, KAI staff and Resource Planning Associates (RPA) staff who were contracted to collect the accumulation data over a two-month period. The purpose of the visit was to select accumulation test areas that were representative of the various on-going yard activities.

Nine test sites were identified within three different yard activity areas with three test sites for each activity area. The activity areas were the alleyways between stored containers, the alleyways between parked trailers and the area beneath the trailers themselves. Each of the test sites was 2000 square feet (190 m^2) in size.

The data collection program was designed as follows:

- three test sites per yard activity area;
- the yard activity areas were named container alleys, trailer alleys and trailer parking;
- all test sites were hand-swept and vacuumed at the start of the two-month test period;
- one of the test sites in each of the yard activity areas was designated as the *Week 1* site, which means each was cleaned or tested every seven days or weekly;
- another one of the sites in each of the yard activity areas was designated as the *Week 2* site, which means each was cleaned or tested every two weeks; and
- the last of the test sites in each of the yard activity areas was designated as the *Week 4* site, which means that each was cleaned or tested every four weeks or monthly.

The program was designed to run over a two-month period. Forty-five samples would be collected over this period provided that dry pavement conditions existed on the designated sampling days which means no rainfall interference. Dry pavement conditions are needed to conduct the hand sweeping and mechanical vacuuming procedures needed to collect the samples.

The program began on May 31, 1996, and ran through July 30, 1996. Thirty-nine samples were collected. No measurable rainfall occurred for the first thirteen days of the program. Rainfall interference in mid to late July reduced the number of *Week 1* samples taken at each activity area to six instead of the eight that were initially planned.

A rainfall gauge was initially installed at the T-5 Yard. However, it was destroyed a few weeks into the data collection program. Hourly rainfall data collected nearby at SeaTac International Airport was used for the model calibration.

18.2.1 Mechanical Analyses

AGI Technologies of Portland, Oregon provided the mechanical analyses of the yard dirt samples under contract to KAI. All work was performed in general accordance with the appropriate American Society for Testing and Materials (ASTM) test methods except where procedures were modified as required by the Scope of Work. To assure consistency, all sieving and subsequent weighing was by the same individual of AGI's staff.

Mechanical grain size analysis was performed on 39 samples provided by KAI. The dry weights for each of the eight sieve fractions were totaled and compared to the sample net dry weight. Weight gain (loss) was noted. All testing was accomplished with stainless steel equipment provided by KAI. All weights were measured in SI units to two significant figures (nearest 0.01 gram). The results of the mechanical analyses for the container alley activity area are presented in Table 18.1. (Note that because of space limitations, the results of the mechanical analyses for the trailer alley and trailer parking areas have not been presented.)

18.2.2 Chemical Analyses

After the mechanical analysis, samples were recombined into three fractions in labeled sealed plastic bags for chemical analyses by others. These composite samples were constructed and labeled as shown:

1. <63 microns, *F* for Fine,
2. 63 to 250 microns, *M* for Medium, and
3. 250 to 6370 microns, *C* for Coarse.

The portion greater than 6370 microns was discarded.

AMTEST, Inc. of Beaverton, Oregon provided the chemical analyses of the composite yard dirt samples under contract to KAI. All work was performed in general accordance with the appropriate EPA test methods.

The three combined fractions (i.e. F, M and C) of four separate samples taken from each of the three activity areas were tested for ICP-Metals (EPA 6010) and total petroleum hydrocarbons (TPH) (EPA 418.1M). The initial samples collected on May 31, 1996 were tested along with the first Week 1, Week 2 and Week 4 samples collected on June 5, 1996, June 13 and 14, 1996 and June 27, 1996, respectively. The three combined fractions of two separate samples taken from each of the three activity areas were also tested for chemical oxygen demand (COD) (EPA 410.4), ortho phosphorus (EPA 365.3) and total kjeldahl nitrogen (TKN) (EPA 351.3). The initial samples collected on May 31, 1996 were tested along with the first Week 4 samples collected on June 27, 1996. A summary of these chemical results is shown in Table 18.2. Although the ICP-Metals analysis provided results on thirty-three different metals, Table 18.2 only includes a summary of the results for copper, lead and zinc.

Several months after the model study described in the next section was underway, it was determined that some additional chemical analyses were needed. The topic of interest was the occurrence and magnitude of dissolved metals and total versus ortho phosphorus in combined fractions (i.e. F, M and C) of samples obtained from each of the activity areas.

Table 18.1 Accumulated sediment by particle size (from container alley sampling area, Seattle WA).

						Particle Size Groups and Diameters (microns)							
Sample #	Date	Type	Area (sq. ft.)	Total (gms)	Total (lbs/ac)	1 <63	2 63-125	3 125-250	4 250-600	5 600--1000	6 1000-2000	7 2000-6370	8 >6370
3	5/31/96	Initial	6000	6356.20	102	5.1%	20.0%	38.3%	18.6%	13.9%	3.1%	0.9%	0.2%
6	6/5/96	Week-1	2000	812.20	39	0.7%	2.9%	9.1%	29.3%	19.3%	22.0%	12.6%	4.0%
7	6/13/96	Week-1	2000	851.40	41	0.3%	1.1%	3.5%	27.7%	30.5%	24.8%	8.4%	3.7%
13	6/21/96	Week-1	2000	979.00	47	0.2%	1.2%	5.8%	34.3%	28.1%	19.7%	7.3%	3.2%
16	6/27/96	Week-1	2000	699.20	34	0.6%	3.4%	10.1%	29.5%	21.8%	20.2%	11.8%	2.8%
27	7/5/96	Week-1	2000	558.50	27	0.2%	1.2%	5.9%	31.9%	25.1%	20.9%	10.7%	4.0%
30	7/10/96	Week-1	2000	1282.30	62	1.0%	6.8%	21.0%	38.3%	15.2%	9.3%	4.7%	3.7%
8	6/13/96	Week-2	2000	1091.00	52	0.2%	1.1%	4.4%	25.3%	27.2%	26.8%	10.1%	5.0%
21	6/27/96	Week-2	2000	1404.50	67	0.4%	3.0%	9.2%	28.0%	25.4%	22.4%	8.2%	3.5%
33	7/10/96	Week-2	2000	1081.80	52	0.8%	7.0%	20.6%	35.8%	16.2%	10.9%	4.8%	3.9%
34	7/28/96	Week-2	2000	1530.40	73	0.4%	2.7%	8.7%	28.0%	25.3%	19.9%	5.5%	9.4%
24	6/27/96	Week-4	2000	1897.50	19	0.4%	2.5%	7.8%	26.5%	26.8%	25.7%	9.2%	1.1%
35	7/28/96	Week-4	2000	2440.60	117	0.5%	2.2%	7.5%	27.0%	23.0%	23.8%	7.5%	8.6%
				Average	61.8	0.8%	4.2%	11.7%	29.2%	22.9%	19.2%	7.8%	4.1%

Table 18.2 Accumulated sediment composition.

Parameter	Average Mass Fraction (mg/kg)					
	Fine	(# tests)	Medium	(# tests)	Coarse	(# tests)
Total Copper	248	(12)	161	(12)	263	(12)
Total Lead	442	(12)	220	(12)	94	(12)
Total Zinc	2167	(12)	1892	(12)	858	(12)
TPH	9492	(12)	6832	(12)	3935	(13)
COD	165000	(6)	65000	(6)	30100	(6)
Ortho Phosphorus	500	(6)	337	(6)	222	(6)
TKN	989	(6)	521	(6)	276	(6)

TPH = Total petroleum hydrocarbon
COD= Chemical oxygen demand
TKN= Total kjeldahl nitrogen

To determine the magnitude of dissolved pollutants within specific particle size ranges of accumulated yard dirt, TCLP Metals (EPA 1311) tests were run for copper, lead and zinc for the combined fractions of several samples from each of the activity areas. In addition, chemical analyses for ortho phosphorus (EPA 365.3) and total phosphorus (EPA 365.2) were conducted on the same samples.

A summary of these chemical results is presented in Table 18.3. It is interesting to note that dissolved metals were found to exist in all three of the yard dirt fractions. In fact, the medium fraction (i.e. 63 to 250 microns) had dissolved metals concentrations that equaled or exceeded those observed from the fine fraction (i.e. less than 63 microns). This data clearly suggests that if significant amounts of fine, medium and coarse yard dirt could be removed by a sweeper in the dry state before rainfall interacts with it, soluble as well as particulate metals will be removed.

Table 18.3 Accumulated sediment leaching potential.

Parameter	Average Concentration					
	Fine	(# tests)	Medium	(# tests)	Coarse	(# tests)
TCLP Metals (dissolved mg/kg TSS)						
Copper	0.23	(6)	0.35	(6)	0.11	(6)
Lead	0.5	(6)	0.62	(6)	1.33	(6)
Zinc	32	(6)	38	(6)	14	(6)
Mass Concentrations (ppm)						
Total Phosphorus	563	(6)	364	(6)	298	(6)
Ortho Phosphorus	610	(6)	413	(6)	257	(6)

This observation is quite significant since wet vaults are essentially ineffective at removing dissolved pollutants, whereas high efficiency sweeping may be able to significantly reduce the magnitude of soluble pollutants like metals found in stormwater. Similar observations could be made for ortho phosphorus especially when it is compared to total phosphorus as shown in Table 18.3.

18.3 SIMPTM Overview

This study used the SIMplified Particulate Transport Model (SIMPTM) (Sutherland and Jelen, 1993) stormwater quality model, a continuous self-contained stormwater quality simulation model that can accurately simulate the stormwater pollutant loadings and expected load reductions from BMPs such as street sweeping and using and cleaning sediment trapping catchbasins and manholes. SIMPTM is unique in its ability to simulate the accumulation, washoff and BMP removal of sediment and associated pollutants (Sutherland and Jelen, 1996a). Other applications of the model have demonstrated its ability to simulate the observe pollutant loads and concentrations from gauged urban basins such as those monitored for the City of Portland's National Pollution Discharge Elimination System (NPDES) stormwater permit and the City of Bellevue's NURP (Sutherland, 1991).

18.3.1 Washoff and Accumulation

SIMPTM divides hourly precipitation records into rainfall events and provides monthly and annual statistics for later analysis. For each rainfall event, it computes a runoff hydrograph, used to continually simulate sediment and bound pollutant transport using the Yalin-Einstein and Foster-Meyer equations, to simulate the capacity of the hydrograph to transport available accumulated sediment from paved areas.

The model also accounts for sediment deposition, armoring, and resuspension processes. Between events, SIMPTM calculates dry deposition processes, and models scheduled-cleaning of streets, parking lots, catchbasins, or maintenance hatches. Overall removals from these practices are provided by SIMPTM based upon measurable data, rather than as user-supplied input such as required by most stormwater quality models. Any excess sediment remains available for further transport simulation, so that actual accumulations may often exceed the *equilibrium* load previously assumed by many to be a *maximum* limit to accumulation.

For a more detailed description of SIMPTM and a discussion of how it was recently calibrated to an extensive NPDES data set collected in Portland, Oregon, the reader is referred to Sutherland and Jelen (1996a).

18.3.2 Sweeper Pickup Performance

The SIMPTM program can accurately simulate this complicated interaction of accumulation, washoff, and street sweeper pickup that occurs over a period of time. The street sweeping component of the SIMPTM model was based on the results of Pitt's street sweeping study conducted in San Jose, California (Pitt, 1979). This model was confirmed in additional studies conducted in Alameda County, California (Pitt and Shawley, 1982) and in Washoe County, Nevada (Pitt and Sutherland, 1982).

These studies found that sweeping removes little, if any material below a certain base residual which was found to vary by particle size. Above that base residual, the street sweeper removal efficiency was described as a straight line percentage, which varied by particle size.

Equation 18.1 illustrates the street cleaning equation used by SIMPTM. For each of eight size groups, the amount removed (*Prem*) is proportional to the initial accumulation (*Po*) in excess of a base residual (*SSmin*) by a sweeping efficiency (*SSeff*):

$$\text{Prem} = \text{SSeff} * (\text{Po} - \text{SSmin}), \quad \text{Po} > \text{SSmin} \qquad (18.1)$$

Therefore, to describe a unique street sweeping operation, one simply needs to know the operations' *SSmin* and *SSeff* values for each of the eight particle size ranges simulated by SIMPTM. Note that *SSeff* is dimensionless, while the dimension of SSmin must match that for accumulation, pounds per curb mile or pounds per paved acre.

For a detailed discussion of the model's accuracy in simulating pickup performance and the actual calibrated input values for various street sweeping operations, the reader is referred to Sutherland and Jelen (1997).

18.3.3 Sediment Trapping Catchbasins

Very little research has been conducted on the sediment retention effectiveness of sediment trapping inlets or catchbasins. However, experiments by Lager et al. (1977) concluded that sediment accumulation in catchbasins is a function of the incoming sediment sizes, the catchbasin volume available to trap sediment, and the runoff flow rate entering the catchbasin. As expected, the larger particles had the highest retention percentage.

An initially clean catchbasin would retain approximately 45% of the incoming sediment until it became about half full. The efficiency then quickly drops to 0 as the trap fills to 60%. This critical point was defined as the breakthrough point. SIMPTM uses Equation 18.2 to relate the capture rate for each group to the retention rate (*X*), or flow over available trap storage, exponentially as follows:

$$\text{Capfrac} = 1/2(1 - A_{trap}X^{Btrap}) \tag{18.2}$$

The two-parameter set A_{trap} and B_{trap} are coded into the program. Each set of eight size-group values (i.e. A_{trap} and B_{trap}) can be redefined. The default parameters for A_{trap} and B_{trap} currently used by the program were based on a calibration of the SIMPTM model to the extensive Bellevue NURP data set (Sutherland, 1991).

18.4 SIMPTM Calibration

As noted in the previous section, the SIMPTM program has the ability to simulate the accumulation and washoff of sediments and their associated pollutants. The model calibration process generally involves the adjustments of parameter values to reproduce observed runoff volumes and pollutant loads. However, since no end-of-pipe stormwater flow and pollutant concentration data was obtained, the calibration focused on reproducing the observed sediment accumulations for each of the activity areas during the two-month sampling period.

Using the hourly rainfall data observed at the SeaTac International Airport during the two-month sampling period, approximately eight runoff producing rainfall events were identified. Runoff producing rainfall events were those events that satisfied one of the following three minimum criteria:

- 0.05 inches (1.3 mm) in one hour ,
- 0.08 inches (2.0 mm) in three hours, or
- 0.10 inches (2.5 mm) in six hours.

SIMPTM modeled rainfall losses using a single-parameter exponential curve that varied with rainfall depth. Once the maximum loss was specified, the exponential rate was automatically set so that the loss matched rainfall at the start of an event. This rainfall loss, which depends mainly on pavement texture or condition, was set to the value recently calibrated from Portland, Oregon runoff data – 0.05 inches (1.3 mm).

The observed sampling event was simulated by the model to be a *perfect* sweeping event in which the minimum residuals (*SSmin*) are zero and the sweeper pickup efficiencies (*SSeff*) were all 100%. A *perfect* sweeping event was simulated by SIMPTM on each of the days in which an accumulation sample was obtained.

With all the washoff parameters set and all but one of the accumulation parameters set to reasonable values observed during other calibrations, the accumulation rate was varied for each of the three activity areas until one uniform rate was found to provide the best overall match. The best overall match was determined by visually examining the model's simulated sediment accumulation values (lbs/acre) against the actual sample weight that was obtained. Each activity area had three test sites that represented the three allowable accumulation periods of one week, two weeks and four weeks, described earlier.

The results of the calibration for the container alley activity area are presented in Figure 18.1. (Note that this figure has 12 calibration points). The calibration focused a greater weight on matching the two *4-Week* calibration points in each of the three activity categories. These were the longest duration calibration points that provided the greatest amount of rainfall and associated washoff interaction. In fact, eight washoff events occurred during the accumulation-monitoring period. The figure shows the model's simulation of these eight washoff interactions. Washoff interaction is extremely important in the application of the calibrated model since the modeling objective was to simulate the stormwater pollutant loads that would occur annually from a hypothetical marine container storage yard. (Note that because of space, the calibration figures for the trailer alley and trailer parking areas are not presented.)

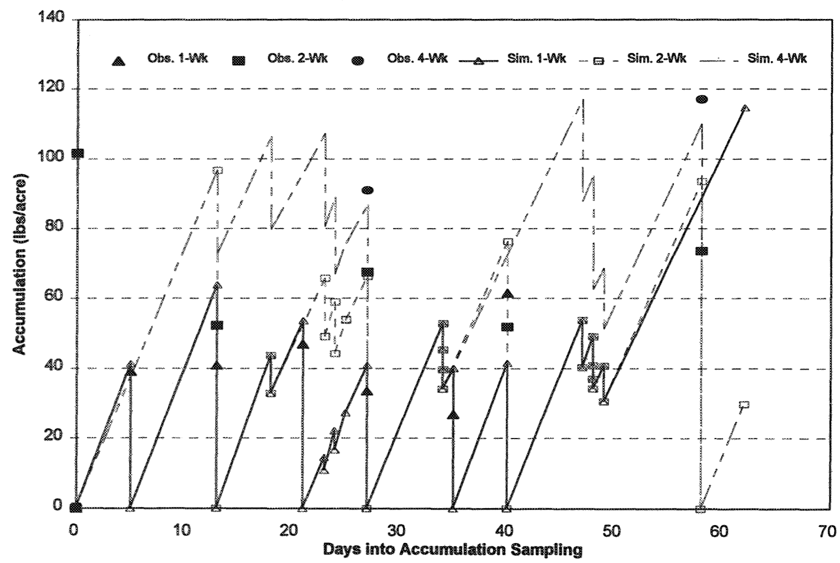

Figure 18.1 Accumulation rate - container alley sampling area.

18.5 Annual TSS Load Reductions from BMPs

Using the calibrated model parameters from each of various activity areas, average annual total suspended solids (TSS) loadings were simulated using an average year of rainfall events.

18.5.1 Average Rainfall Year Development

Rather than simulate many runs using many years and summarize the extensive results, a long rainfall record was processed into many years of events, which were then evaluated. The twelve *best* months were combined to synthesize an average year, and used for the annual runs to evaluate different BMP practices.

High quality, continuous hourly rainfall data has been collected and recorded by the National Oceanic and Atmospheric Administration (NOAA) at SeaTac International Airport since 1965. Data through 1993 was obtained on CD-ROM and used in this study. Using the depth versus time criteria presented earlier, hourly rainfall was processed using RAINEV (a rainfall analysis program included in the SIMPTM package) into discrete events that were summarized by the following parameters for each month of each year:

1. number of events;
2. total duration of events;
3. total depth of events;
4. maximum hourly rainfall;
5. average intensity (i.e. total depth/total duration); and
6. average dry time preceding events

These were then analyzed graphically in a spreadsheet month by month. Figure 18.2 shows an example for April. Each statistic for each year was compared to its average for all years. The *absolute error* or *departure from the mean* was graphed by year, with emphasis on the total monthly depth. Months

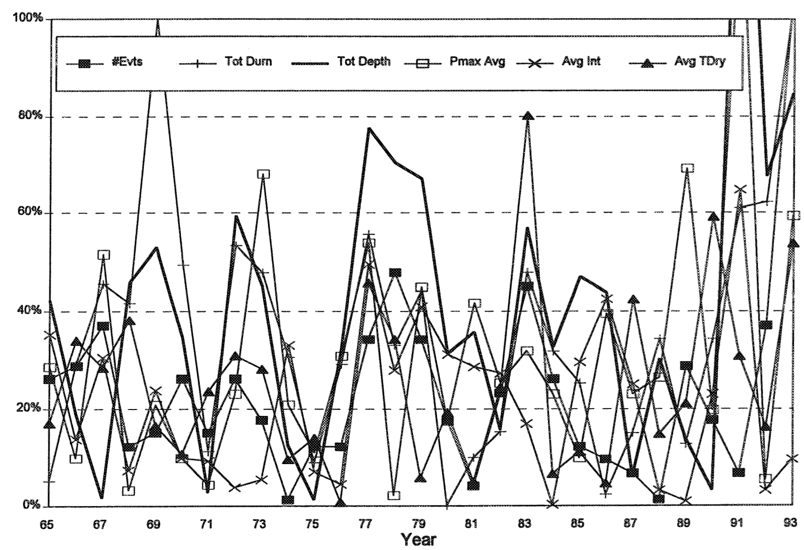

Figure 18.2 Synthetic rainfall year synthesis - April.

that closely approximate the mean were found by looking for years where all data points (i.e. *errors*) neared *0*. In this example, statistics for April of 1975 clearly are nearest those for all Aprils, since all lines are very close to *0*. So, April 1975 was the April rainfall record used to construct the average or representative year.

In this manner, each of the twelve months was examined and the *best* month for each month was found. The hourly data for each were then combined to create a representative, average year, which was analyzed by RAINEV to generate the events used by SIMPTM in its average annual runs.

Table 18.4 presents the resulting composition and compares the monthly, seasonal, and annual rainfall depths for the whole record to those for this average year and those resulting if just an actual year like 1980 (rather than individual months) had been used. The average year is clearly more representative. Figure 18.3 supports this conclusion by graphing the monthly rainfall depths associated with each of these three potential data sets. The average year monthly depths are nearly indistinguishable from the averages for the entire record.

Table 18.4 Synthetic year construction. (Sea-Tac International Airport, WA hourly data).

Period	Year used in model	Model	Average	1980 only
Annual		35.77	35.90	35.38
January	1976	5.55	5.28	4.23
February	1974	4.00	3.95	4.68
March	1988	3.75	3.62	2.10
April	1975	2.49	2.46	3.23
May	1976	1.61	1.62	0.97
June	1974	1.25	1.30	1.77
July	1979	0.73	0.79	0.46
August	1972	1.13	1.12	0.64
September	1988	1.75	1.83	1.43
October	1989	2.98	3.07	1.54
November	1982	5.31	5.33	6.94
December	1987	5.22	5.52	7.39

18.5.2 TSS Loadings

Using the calibrated model parameters from each of three activity areas, the model was used to simulate the sediment and associated pollutant accumulation and washoff that would occur over an average year from a hypothetical 10-acre (4 ha) container yard. As presented above, the average precipitation year was obtained from a detailed statistical analysis of a 29-year precipitation record at SeaTac International Airport.

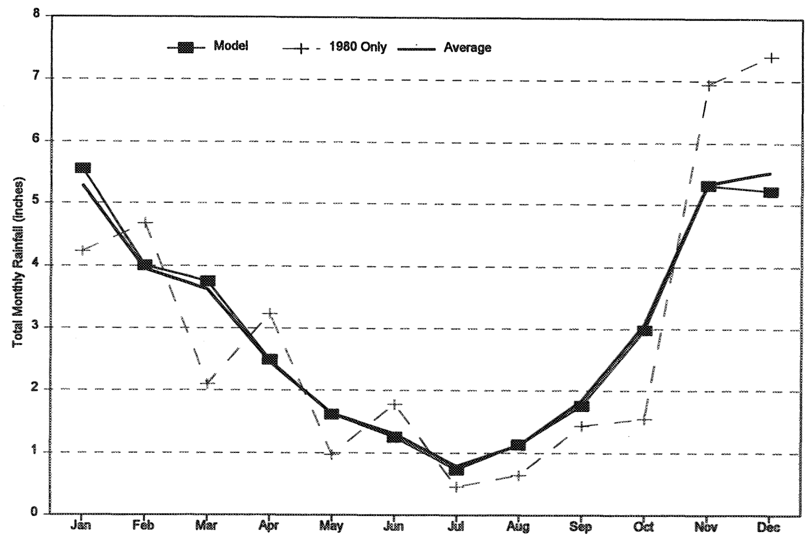

Figure 18.3 Synthetic rainfall year depths.
(Sea-Tac International Airport hourly rainfall data).

The model simulations dealt with alternative frequencies of sweeping (e.g. daily to monthly) and catchbasin cleaning (monthly to annually), along with alternative sizes of catchbasins (e.g. normal, at 10 cubic feet (0.3 m^3) per 15,000 ft^2 (1390 m^2) of area; or enlarged, at 37.8 cubic feet (1.07 m^3) for the same area).

The hypothetical 10-acre composite site or container storage yard was composed of five different activity areas. Area *A* was 5.0 acres (2 ha) in size and consisted of trailer and container alleys, roadways, parking lots, loading docks and entrance and exit areas. All of this area was assumed to be accessible to sweeping or *sweepable* and all of this area was assumed to be accessible to rainfall or *washable*. Area *C* was 0.5 acres (0.2 ha) in size and consisted of container storage areas that are both *sweepable* and *washable* which was only half of the actual container storage area of 1.0 acres (0.4 ha) within the composite site.

Area *T* included trailer parking and storage areas that were only 8% *sweepable* and 21.8% *washable*. This 21.8% represented the 8% that was assumed vacant at any given time and the remaining 13.8% that was the area between parked trailers. Area *X* was the *unsweepable* fringe area of 0.5 acres (0.2 ha) between the ends of the trailer rows which is assumed to be *washable*. Area *O* represented those areas (3.31 acres or 1.35 ha total) that the model assumed would contribute runoff but no pollutants, and included roof tops (1.0 acre or 0.4 ha), the tops of stored containers (0.5 acres or 0.2 ha), and the tops of parked trailers (1.81 acres or 0.74 ha).

18.5.3 Dry Versus Damp Pavement Sweeping

As stated earlier, the computer simulation considered the effect of sweeping frequency on the reduction of pollutants in individual storms that occur throughout an average precipitation year. It also considered the effects of rainfall periods on both the ability to sweep and the efficiency of the sweeper. Rainfall periods are of three types - dry period (high sweeping efficiency), rainy periods that produce runoff (sweeping cannot occur), and rain periods that cause damp pavement conditions without runoff (sweeping occurs but at reduced pickup efficiency).

Unfortunately, the computer model does not have the ability to alter the basic performance characteristics of the sweeper during a simulation. So, two sets of model simulations were obtained – one using performance characteristics of damp pavement sweeping, and a second using those of dry sweeping. Portions of the simulated TSS washoff loads from the hypothetical 10-acre (4 ha) composite site are presented in Tables 18.5 and 18.6.

The results clearly show that sweeping could provide significant reductions in TSS loadings especially at scheduled frequencies of seven days or less. Also, the simulated reductions suggest enlarged catchbasins or large inlet sumps with 37.8 ft^3/15,000 ft^2 (1.07 m^3/1390 m^2) do not appear to be worth the added cost. Normal catchbasins with 10.0 ft^3/15,000 ft^2 (0.3 m^3/1390 m^2) cleaned annually appeared to provide reasonably good TSS load reductions when combined with frequent high efficiency sweeping.

Note that as regards damp- and dry-pavement sweeping, SIMPTM does not simulate sweeping during periods of actual runoff. Thus for damp- and dry-pavement results in Tables 18.5 and 18.6, SIMPTM used the pickup performances of damp pavement or dry pavement, respectively, throughout the entire annual simulation, but skipped sweeping events that fell during rain events.

Since damp pavement conditions will occur on occasion throughout the year, one can probably assume that the actual pollutant removal effectiveness would be somewhere between the corresponding model simulation removals for damp and dry conditions.

Dry pavement sweeping pickup performance was based on the *SSmin* and *SSeff* characteristics found for the Enviro Whirl I dry sweeper tests. Damp pavement sweeping pickup performance was based on the *SSmin* and *SSeff* characteristics for the tandem operation which included the use of a tanker truck that sprayed water on the street surface just before it was swept by both a mechanical and vacuum sweeper.

It is noted that the modeled difference between these two sweeping conditions (i.e. damp or dry pavement) is not very significant. This is due primarily to the overland washoff hydraulic characteristics which are very sensitive to the sweepers removal of coarse particles (i.e. 250 microns or greater)

Table 18.5 Annual TSS loadings - dry pavement sweeping. (pounds per acre per year, varied sweeping or inlet sumps, Seattle, WA).

Envirowhirl Sweeping Interval (days)	Cleaning Interval for Sediment Trapping Catch Basins (days)						
	Not Used	Normal Inlets (10 cuft / 15,000 sft) 360	180	90	Large Inlets (37.8 cuft / 15,000 sft) 360	180	90
A - Pier 5 Trailer and Container Alleys, Roadways, and Parking Lots							
0	2505	1655	1335	1324	1293	1291	1290
30	2024	1184	1076	1070	1045	1044	1043
15	1621	879	862	859	837	837	836
7	1076	576	572	571	556	556	556
3.5	786	419	417	417	407	406	406
2	469	251	250	250	243	243	243
1	251	135	134	134	131	130	130
C - Pier 5 Container Storage Areas (50% Sweepable & Washable)							
0	3935	3074	2356	2270	2148	2134	2129
30	3573	2721	2117	2061	1950	1938	1934
15	3251	2399	1916	1877	1775	1765	1762
7	2563	1712	1498	1479	1399	1393	1391
3.5	2035	1250	1184	1174	1110	1106	1105
2	1470	870	854	850	803	801	800
1	877	515	511	509	480	480	479
T - Pier 5 Trailer Parking & Storage Areas (8% Sweepable, 21.8% Washable)							
0	4062	3202	2452	2349	2220	2204	2199
30	3933	3075	2359	2273	2149	2134	2129
15	3808	2950	2274	2201	2081	2067	2062
7	3481	2624	2061	2010	1900	1890	1886
3.5	3117	2262	1833	1799	1701	1692	1689
2	2650	1798	1549	1529	1445	1440	1437
1	1957	1178	1137	1128	1066	1064	1062
X - Pier 5 Unsweepable Fringe between Ends of Trailers							
0	3832	2971	2282	2207	2090	2076	2071
COMPOSITE SITE, Total Lbs 10-acre site coposed of: (5.0 A, 0.5 X, 0.5 C, 0.69 T, 3.31 "0")							
0	19209	13509	10685	10477	10115	10080	10067
30	16536	10887	9207	9051	8726	8697	8687
15	14272	9118	7978	7854	7555	7530	7521
7	10978	7032	6171	6082	5837	5818	5811
3.5	9017	5768	5085	5016	4806	4791	4785
2	6827	4415	3888	3833	3660	3648	3644
1	4960	3229	2854	2808	2673	2664	2661

which is quite good in both cases. Since both sweeping operations (i.e. damp versus dry) are also considered quite effective in the pickup of mid range particles (i.e. 63 to 250 microns), the net effects of the greater pickup performance for the fine material (i.e. less than 63 microns) is not that great.

Table 18.6 Annual TSS loadings - damp pavement sweeping. (pounds per acre per year, varied sweeping or inlet sumps, Seattle, WA).

Tandem Sweeping Interval (days)	Cleaning Interval for Sediment Trapping Catch Basins (days)						
	Not Used	Normal Inlets (10 cuft / 15,000 sft)			Large Inlets (37.8 cuft / 15,000 sft)		
		360	180	90	360	180	90
A - Pier 5 Trailer and Container Alleys, Roadways, and Parking Lots							
0	2505	1655	1335	1324	1293	1291	1290
30	2082	1241	1110	1103	1077	1075	1075
15	1714	939	916	912	888	887	887
7	1255	683	676	674	654	654	653
3.5	992	542	538	537	520	519	519
2	720	399	397	396	381	381	381
1	537	304	302	302	288	288	288
C - Pier 5 Container Storage Areas (50% Sweepable & Washable)							
0	3935	3074	2356	2270	2148	2134	2129
30	3586	2734	2123	2066	1955	1944	1940
15	3273	2420	1926	1886	1785	1775	1772
7	2629	1777	1532	1512	1432	1426	1424
3.5	2142	1333	1243	1232	1166	1162	1161
2	1631	967	946	940	889	887	886
1	1110	654	647	645	608	607	607
T - Pier 5 Trailer Parking & Storage Areas (8% Sweepable, 21.8% Washable)							
0	4062	3202	2452	2349	2220	2204	2199
30	3937	3079	2361	2275	2151	2136	2131
15	3816	2958	2278	2204	2084	2071	2066
7	3504	2647	2073	2021	1912	1901	1897
3.5	3159	2304	1856	1820	1722	1713	1710
2	2723	1870	1589	1567	1483	1477	1475
1	2086	1268	1211	1200	1135	1132	1131
X - Pier 5 Unsweepable Fringe between Ends of Trailers							
0	3832	2971	2282	2207	2090	2076	2071
COMPOSITE SITE, Total Lbs 10-acre site coposed of: (5.0 A, 0.5 X, 0.5 C, 0.69 T, 3.31 "0")							
0	19209	13509	10685	10477	10115	10080	10067
30	16837	11180	9382	9223	8889	8860	8848
15	14755	9434	8257	8128	7816	7791	7781
7	11921	7618	6719	6625	6350	6330	6323
3.5	10128	6454	5735	5661	5415	5398	5392
2	8210	5254	4695	4635	4418	4405	4400
1	6596	4206	3812	3764	3573	3563	3559

Dramatic changes in performance may occur between damp and dry sweeping when occasional concentrated runoff conditions like gutter flow or swale flow are present on the site. It is important that the Port Authority uses for any field testing or actual program implementation, the most efficient pavement sweeper that is known to exist which is the Enviro Whirl dry sweeper manufactured by Enviro Whirl Technologies, Inc. of Centralia, Illinois (recently changed to Schwarze-Enviro Whirl).

18.6 Annual Pollutant Loads

Sediment washoff was related to washoff of other pollutants by mass-fractions or potency factors assigned to each of the eight particle size groups of accumulated sediment. These are generally set from observed fractions of accumulated sediment or from observed sediment washed off during sampled events. Since no washoff data was obtained, the pollutant simulations were based on the chemical analyses of the collected samples.

As discussed earlier, chemical analyses of yard dirt samples were conducted for many pollutants. It was determined that in addition to TSS the SIMPTM pollutant simulations would include copper, lead, zinc and phosphorus. The simulation of the particulate or suspended fraction of each pollutant was based on the mean potency factors found in the yard dirt analyses. The soluble fraction of each pollutant was based on the following assumptions: 50% of the copper, phosphorus and zinc washoff at any given time is soluble, while only 20% of the lead washoff is soluble. It was assumed that the sweeper could prevent the washoff of soluble pollutants but that catchbasins and wet vaults could not remove any soluble pollutants.

The results of these model simulations were then compared to the results obtained from the simulated performance of a wet vault designed according to the Puget Sound water quality criteria. This criteria would require a 50,000 ft^3 (1400 m^3) stormwater storage area needed to serve the hypothetical 10 acre (4 ha) container yard. The sediment and associated pollutant removals of the wet vault were based on a set of modified Stokes' Law equations to compute settling velocities for various sizes of transported sediments. These calculations were processed in a spreadsheet using outputs from the SIMPTM model as the starting point.

The results of the SIMPTM pollutant simulations for the average rainfall year are presented in Tables 18.7 and 18.8. As stated earlier, both dry pavement sweeping and damp pavement sweeping were simulated separately. Sweeping intervals were held to 30, 15, 7, and 3.5 days, respectively. The 3.5-day interval is the average between a 3-day and 4-day simulation.

Table 18.7 Annual pollutant loads - dry pavement sweeping. (Pounds per year, Seattle WA data).

Pollutant Washoff Average Annual Loads		**Baseline** *No Trapping* *No Sweeping*	**Normal WQ Inlets** *Sweeping Interval (days)* *30*	*15*	*7*	*3.5*	**WQ Vault** *Big Inlets* *No Sweeping*
Annual Dissolved Loads (Lbs)							
D-Cu	Copper	4.67	4.00	3.44	2.63	2.16	4.67
D-P	Phosphorus	13.49	11.61	10.01	7.70	6.32	13.49
D-Pb	Lead	0.29	0.25	0.22	0.18	0.15	0.29
D-Zn	Zinc	21.55	18.77	16.40	12.89	10.73	21.55
Annual Suspended Loads (Lbs)							
TSS		19209	8697	7530	5818	4791	1693
S-Cu	Copper	4.67	2.08	1.80	1.38	1.13	0.41
S-P	Phosphorus	13.49	6.09	5.27	4.07	3.35	1.19
S-Pb	Lead	2.61	1.27	1.12	0.90	0.75	0.26
S-Zn	Zinc	21.55	10.22	8.97	7.09	5.92	2.02
Annual TOTAL Loads (Lbs)							
TSS		19209	8697	7530	5818	4791	1693
T-Cu	Copper	9.33	6.09	5.24	4.02	3.29	5.07
T-P	Phosphorus	26.97	17.70	15.29	11.77	9.67	14.68
T-Pb	Lead	2.90	1.52	1.34	1.07	0.90	0.55
T-Zn	Zinc	43.10	29.00	25.38	19.98	16.64	23.57
Annual Percent Removals							
TSS		*reference*	55%	61%	70%	75%	91%
T-Cu	Copper	*reference*	35%	44%	57%	65%	46%
T-P	Phosphorus	*reference*	34%	43%	56%	64%	46%
T-Pb	Lead	*reference*	48%	54%	63%	69%	81%
T-Zn	Zinc	*reference*	33%	41%	54%	61%	45%

18.7 Conclusions

The following study conclusions can be offered:

- For marine cargo handling and storage facilities, the pollutant removals associated with high efficiency sweeping at a weekly frequency in combination with normal catchbasin inlets, cleaned annually are essentially equivalent to those removals obtained by wet vaults.

Table 18.8 Annual pollutant loads - damp pavement sweeping.
(Pounds per year, Seattle WA data).

Pollutant Washoff Average Annual Loads		Baseline *No Trapping No Sweeping*	Normal WQ Inlets *Sweeping Interval (days)* 30	15	7	3.5	WQ Vault *Big Inlets No Sweeping*
Annual Dissolved Loads (Lbs)							
D-Cu	Copper	4.67	4.07	3.56	2.85	2.40	4.67
D-P	Phosphorus	13.49	11.81	10.35	8.35	7.08	13.49
D-Pb	Lead	0.29	0.26	0.23	0.20	0.17	0.29
D-Zn	Zinc	21.55	19.16	17.03	14.16	12.26	21.55
Annual Suspended Loads (Lbs)							
TSS		19209	8860	7790	6330	5398	1693
S-Cu	Copper	4.67	2.12	1.86	1.50	1.27	0.41
S-P	Phosphorus	13.49	6.21	5.45	4.42	3.77	1.19
S-Pb	Lead	2.61	1.29	1.17	0.99	0.87	0.26
S-Zn	Zinc	21.55	10.44	9.32	7.81	6.79	2.02
Annual TOTAL Loads (Lbs)							
TSS		19209	8860	7790	6330	5398	1693
T-Cu	Copper	9.33	6.20	5.41	4.34	3.67	5.07
T-P	Phosphorus	26.97	18.02	15.80	12.77	10.85	14.68
T-Pb	Lead	2.90	1.55	1.40	1.18	1.04	0.55
T-Zn	Zinc	43.10	29.60	26.36	21.97	19.05	23.57
Annual Percent Removals							
TSS		*reference*	54%	59%	67%	72%	91%
T-Cu	Copper	*reference*	34%	42%	53%	61%	46%
T-P	Phosphorus	*reference*	33%	41%	53%	60%	46%
T-Pb	Lead	*reference*	46%	52%	59%	64%	81%
T-Zn	Zinc	*reference*	31%	39%	49%	56%	45%

- Sweeping/catchbasin effectiveness appears to be comparable to wet vault effectiveness even though a sweeper is unable to access the entire container yard, because of the presence of parked container trailers, which cannot be moved to accommodate the needs of sweeping.
- Wet vaults are able to remove only sediment and the associated particulate pollutants. They are not able to remove soluble pollutants. In contrast, high efficiency sweepers are able to remove soluble pollutants since this fraction is contained in the accumulated sediment and can be removed by the sweeper during dry periods.

- TSS is the characteristic of stormwater that is commonly used to compare the performance of alternative stormwater BMP's. Sweeping may be unable to achieve the high TSS removal efficiency simulated for wet vaults.
- High efficiency sweeping may be more efficient than wet vaults in the removal of pollutants that tend to have a significant fraction that is soluble such as copper, zinc, and phosphorus.
- Wet vaults may be more efficient than high efficiency sweeping in the removal of pollutants that tend to have a significant fraction in the particulate state such as lead.

The calculated efficiency of wet vaults is based on modified Stokes' Law to compute settling velocities for various sizes of transported sediment. It is probable that wet vault efficiency is actually lower in practice. As a result, high efficiency sweeping may be considered an even more viable solution under real conditions.

Given the potential uncertainty of the model simulation results presented in Tables 18.5 through 18.8, ranges of possible removal efficiencies are presented in Table 18.9. Also presented in Table 18.9 is the effect of sweeping frequency. With regard to sweeping frequency, the model suggests there may be significant benefit in sweeping weekly as opposed to biweekly. However, there may be little incremental benefit of sweeping twice weekly in comparison to weekly.

Table 18.9 Expected annual pollutant load reductions.

Parameter	Twice Weekly Sweeping	Weekly Sweeping	Biweekly Sweeping	Wet Vaults
TSS	45%-70%	45%-65%	40%-60%	75%-90%
Total Phosphorus	35%-60%	30%-55%	20%-40%	35%-45%
Total Lead	40%-60%	35%-60%	30%-50%	65%-80%
Total Zinc	30%-55%	25%-50%	20%-40%	35%-45%
Total Copper	35%-60%	30%-55%	20%-40%	35%-45%

Note: Normally sized catchbasins are cleaned once during the year.

With regard to overall removal efficiencies, the model simulation results presented in Tables 18.5 through 18.8 include two very reasonable assumptions that are altered to provide the pollutant removal ranges in Table 18.9. First, the model assumes that the sweeper removes the same fractions of soluble pollutants associated with particulate material during damp pavement conditions as it does during dry pavement conditions. This may not be the case since some of the soluble fraction could be dissolved and transported to the catchbasins before it can be swept.

Secondly, the model assumes that material that accumulates under the trailers is not washed from the site since the topography of a container yard is such that stormwater typically does not flow beneath trailers except in extreme events. Nonetheless, the low end of each range presented in Table 18.9 assumed that none of the dissolved pollutants are captured by sweeping during damp-pavement sweeping and that the parked trailers do not block the potential transport of material beneath trailers. Thus more area is allowed to wash directly to the catchbasins, and the vault is given the opportunity to capture this material whereas sweeping is not.

With regard to wet vaults, SIMPTM predicts a removal efficiency of about 90% for TSS (Tables 18.7 and 18.8). This is greater than other predictive methods such as USEPA (1986). The USEPA methodology estimate removal efficiency using rainfall statistics and settling velocity data generated in the NURP study. Based on the concept of the volume specified by the Department of Ecology (1992), the estimated performance according the USEPA (1986) is about 75%. The lower end of the ranges in the removal efficiencies for the wet vault shown in Table 18.9 reflect the somewhat more conservative prediction methods like those documented by the USEPA (1986). What Table 18.9 still indicates is that pollutant removal ranges for sweeping are similar to the ranges for wet vaults for those pollutants that tend to be more soluble such as copper, zinc, and phosphorus.

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